A Novel Mirror Manipulator Design and the Prototype Test

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Abstract:

A new mirror manipulator is introduced in this paper. Although it was designed at the Canadian Light Source for the Far-IR beamline in-vacuum M2 mirror manipulator, it is universal and it can be used for manipulating in-vacuum mirror or be used in atmosphere condition. The concept is stacking three linear motions and three rotations in a compact mechanism. Large radial curved rails or rotation rings are used for the roll, pitch and yaw guide ways. Like the three linear motions, these three rotations are driven by linear actuators. While the linear actuator is tangent to the rotation rails, when the rotation range is within ±1.5°, it is almost linear within 0.01 micron maximum error.

The following are features of this kind of mirror manipulator.

1) The degrees of freedom (DOFs) could be chosen based on the mirror manipulating requirements. When the mirror only needs 3 DOFs, it can be assembled withonly3 DOFs to save cost and increase stability. When it has 6 DOFs, it functions exactly like a Hexapod.
2) Compared to Hexapod, it does not need positioning software. Each actuator exactly controls one degree of freedom. The six degrees of freedom are independent.Furthermore, it is easy to directly limit these three motions.
3) It has high resolution and repeatability(long actuating arm).
4) With small driving units it can manipulate heavy mirrors(the loads perpendicular to the actuating direction).
5) The manipulator could be de-coupled from the mirror chamber and be seated on a granite table independently.

6) The three rotation axes intersect to a single point and this point can be adjusted vertically and horizontally or be fixed to the optical center independent of the mirror's linear motions.

A one DOF (rotation) prototype was built and was tested. The testing result is presentedbelow.

1- The mechanism

The mirror manipulator consists of a combination of XY linear stages, a vertical rotating stage, two horizontal rotating stages and a vertical linear stageas shown in figure 1. Each stage adjusts one degree of freedom of the mirror. They are independent each other. If the mirror does not require 6 degrees of adjustment, the corresponding stage can be simply removed. For example, some mirrors don't require the adjustment along the beamline, thereforethe bottom XYstage of the manipulator can be changed to X stage.

The three rotation axes are designed to intersect to a single point. Usually this point is at the mirror pole. However, different stage configurations can achieve different effects.For example, by putting the vertical stage on top of the rotation stages, the mirror can be moved up and down in wide range, while the rotation center remains fixed on the original elevation. This case is suitable for multi strip mirror manipulating.The mirror working strip can be changedwhile keeping the roll, pitch and yaw centers fixed on the beamline. If the vertical stage is under the rotation stages, the rotation center changes with mirrorvertical movement. This case allows adjusting the rotation center to coincide with the beam line. In the same way, if an X stage is put on top of the rotation stages, two mirrors can be switched horizontally. With this configuration, the lateral movement of the bellows must be considered.

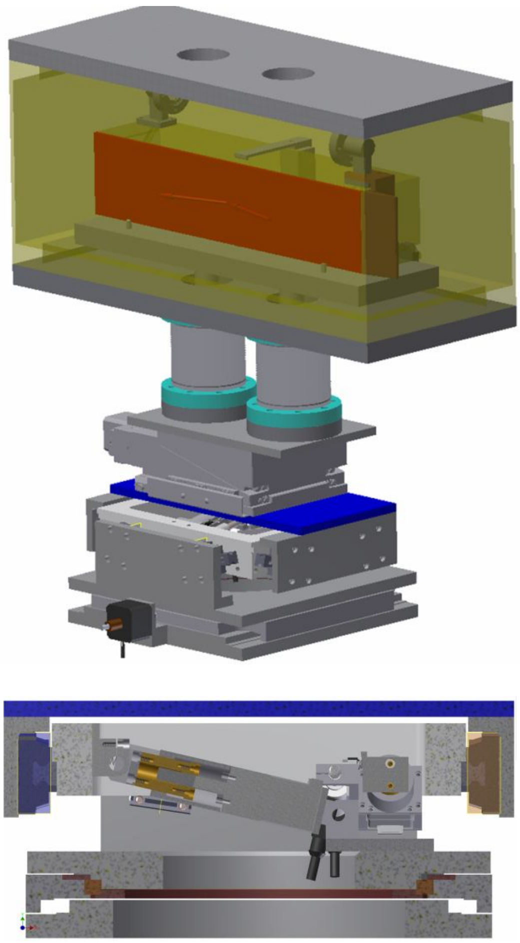

Fig. 1 The manipulator diagram

The three rotation movements are driven by linear actuators. Figure 2 shows the mechanism. The two bottom vertexes of the triangle are flexure bearings. The top vertex is the center of the circular bearing. The bottom edge represents the linear actuator. The lengths of these axes are changeable. The right edge is the fixed frame. The left edge representsthe rotation platform. When the actuator changes ΔL at neutralangle A_0 position, the angle change is A_r.

A_0= (1)

A_r= – A_0(2)

Theoretically, the angle change inAr is not in linear with changes inlength ΔL, butif the rotation is in ±1.0° (±17.45mrad),the relationcan be simply treated as linear.

$A_p = \Delta L / R$ (3)

Figure 3 shows the real angleA_r, proximate angle $A_p$and the angle difference. In the diagram, the horizontal coordinate is the actuator motion in half steps. The vertical coordinateis the angle changing in arc seconds.The difference at 1° rotation is0.1891arcseconds (9.17×10^{-4}mrad). It is much less than the driving system resolution.

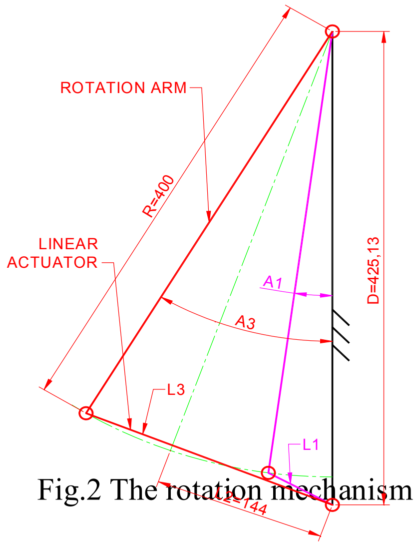

Fig.2 The rotation mechanism

The angular resolution $R_a$can be calculated with function (4). In the function, P isthe actuator driving screw pitch; R is the distance between acting point and the rotation center.

$$R_a = 2.5\frac{P}{R} \text{ (mrad/half step)} \quad (4)$$

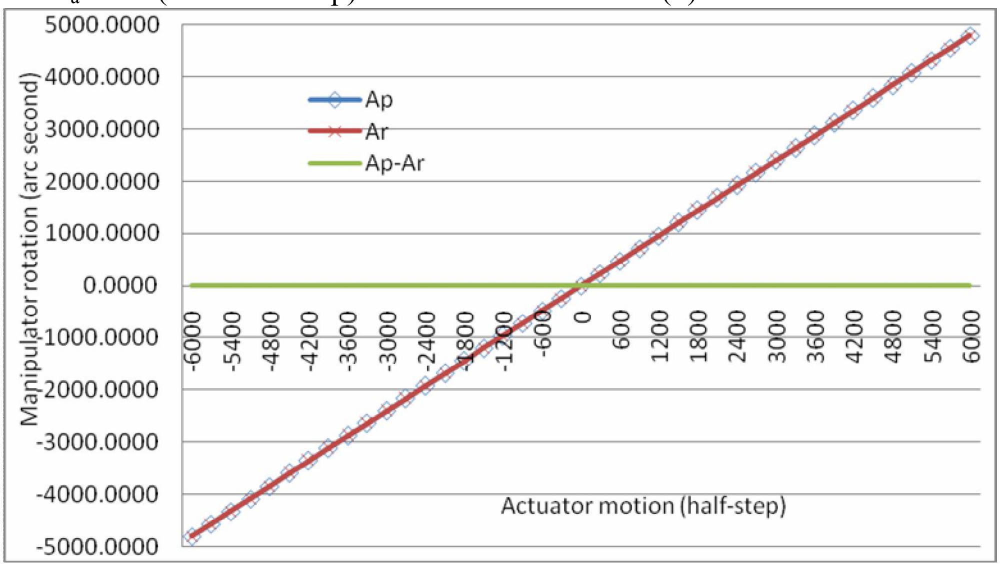

Figure 3 The relation between manipulator rotation and actuator steps

For placing the whole manipulator outside the vacuum chamber and keeping the rotation center on the beamline, the rotation guide way should have a large radius. It could be 300mm to 1000mm. In the prototype design, it is 400 mm. Currently, it is difficult to find such a large diameter precision guide way. For accuracy and repeatability aspects, the cross roller rail is better and it could be preloaded.

If the mirror is inside the UHV chamber and the manipulator is designed be outside the chamber,it can be de-coupled from the chamber and chamber support. For stability, the manipulator is designed to be sitting on a granite block. From the top plate of the manipulator, 2 to 3 fixed rods are inserted into the chamber and support the mirror platform. Accordingly, 2 to 3 bellows are used to seal the vacuum. A single rod with one bellow is not recommended. In this case, the bellow size becomes large and it becomesinflexible.This inflexibility, especially with rotation, will twist the bellow in a way that is not allowed by the bellow supplier.

2-The one dimension prototype and the test result

For testing the rotation mechanism, a one dimension actuator prototype was designed and be tested shown as in figure 4. The rails are THK curved R400 rail. The linear actuator is Haydon stepping linear actuator. The neutral length is 144mm. For simulating the load, a 1:1 dummy mirror was installed in the assembly. A Heidenhainabsolute linear length gage was installed to test the actuator motion and used for close loop control. An autocollimator was installed to test the angle change. Both the absolute encoder and autocollimator output were recorded in the testing.

Thetheoretical linear actuator resolution is 3.1 microns/full step or 1.55 microns/half step.The manipulator angular resolution is1.60 arc seconds/step (7.75micron radians/step), 3.88 micron radians/half step (0.80 are second/half step).

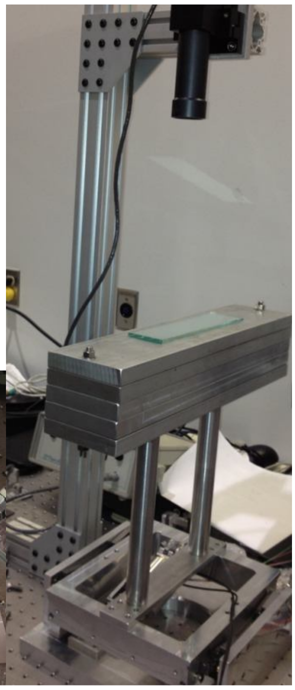
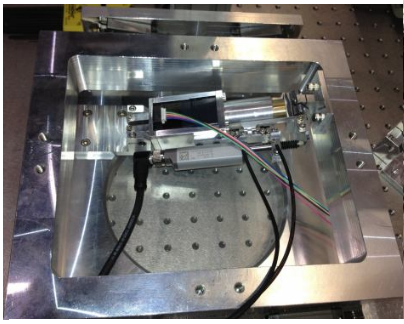

Fig. 4 The one dimension prototype

To test the resolution, two tests were performed. In the first test, the linear stepper motor was driven in half-steps. The resolutions are shown in figure 5. The tested resolution is 1.58μ/half-step or 0.78 arc second/half-step. In the second test, the linear stepping motor was driven in 1/64 micro-stepmode. The test was set driving the motor at one micro-step, 8 micro-steps, 32 micro-steps and 64 micro-steps. The average resolution is 0.05μ/micro-step in linear or 0.024 arc second/micro-step. The tested result shows that when the motor is driven in 1/64, 1/8 full step, the motion is not stable. When the actuator is driven in half or full step, the motion stabilizes.

The backlash and repeatability

When the linear actuator stepping motor was driven in 1/64 micro-step, the manipulator was commanded to walk in +N, -N, -N, +N step cycles. N is the number of micro steps, and it was changed from 100, 200, 300, 400, 500, 1000, 3000, 7000, 10000, 13000, 16000, 19000, 22000.In one cycle, 2 backlash values and one position error can be tested. The average linear backlash is 2.9 micron. The angular backlash is 0.0107mrad (2.2 arc seconds). The position error is between -0.75 to 0.78 micron in linear, and -0.7 to 0.6 arc seconds (-0.0034 to 0.0029 mrad) in angular.

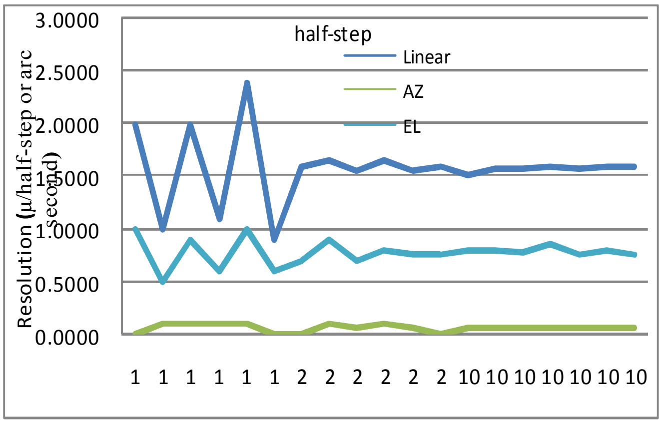

Fig. 5 Tested linear and angular resolutions

3-Conclusion

1. Some preliminary design work was done and a prototype was tested. More R&D work and a real application are necessary. It will be used on CLS FAR IR beamline M2 mirror manipulator.
2. Three factors decide the performance of the manipulator. They are the flexure pivot bearing, the linear actuators and the linear & circular guide rails. The current technology has no issue with these three requirements, but cooperation from industry is required to produce compact and high performance linear actuators and large radius cross roller circular bearings.